COMPLIMENTARY COPY

ontario hydro
research division

To: Mr. D.M. Hayter, Plant Dev. Engineer, D&D - Generation
Mr. J. Graham, Assistant Manager, CNS
Dr. D. Mills, Director of Research

NON-INVASIVE LOCATION OF CHANNEL SPACERS (NILOCS) - MODAL ANALYSIS OF BEAM VIBRATIONS

P.G. Buchan and M.A. Green
Electrical Research Department

ABSTRACT

The NILOCS project was initiated to seek a non-invasive method for determining the locations of garter spring spacers in CANDU fuel channels. Mechanical vibrations provide the only realistic means of carrying information about spacer locations out from the interior of the reactor. Previous reports have described attempts to detect and analyze travelling waves that propagate from the garter springs, along the fuel channel, to the end fittings. Those attempts were not successful, however, primarily due to the many dispersive propagation modes. An alternate approach is to work with standing waves. Beam vibrations of the pressure tube and calandria tube are coupled by the garter springs, so the resonant frequencies depend on the spacer positions. This dependence has been confirmed by experiment and theoretical analysis. Once again, however, the necessary information cannot be reliably determined when given access only to the end fittings. Thus spectral analysis of the beam vibrations is not viable for non-invasive determination of garter spring locations.

1.0 *INTRODUCTION*

A wide range of vibration analysis techniques have been investigated in efforts to develop a non-invasive method for determining the positions of garter spring (GS) spacers in CANDU fuel channels [1-4]. The basic premise has been that mechanical vibrations generated at the GS locations should propagate in both directions along the fuel channel. At the end fittings these signals would be detected with accelerometers or other vibration sensors. Assuming well defined wave velocities, one could then determine the distances from the GS spacers to the two ends of the channel. Frequencies from 300 Hz to 200 kHz were studied but no reliable inspection method could be devised. The principal reasons for failure were lack of a vibration energy source; and a proliferation of dispersive wave propagation modes.

job	file	date	report no.
740617-502-051	826.116	October 14, 1986	86-177-K

Beam vibrations of a fuel channel, at frequencies below 100 Hz, have also been viewed as potential carriers of information about the GS positions. The resonant beam vibrations excited by PHT and moderator flow were investigated in early attempts at predicting contact between the pressure tube (PT) and calandria tube (CT) [5,6]. More recently these vibrations have been studied within the context of condition monitoring [7]. We report here on new experimental and analytical studies based on the imposition of a controlled exciting force.

In the next section we describe the basic properties of the beam vibrations. Results of parallel experimental and analytical studies are presented. This is followed by a discussion of the implications of these results for a non-invasive inspection program. We close with a brief summary and recommendations.

2.0 *FUEL CHANNEL BEAM VIBRATIONS*

At frequencies below ~100 Hz, the dominant vibrations of a fuel channel are transverse, beam-type motions of the pressure tube, calandria tube, and end fittings (EF). Resonant frequencies are determined by the material elastic moduli; EF and tube geometries; the masses of fuel, water, plugs, etc; and by the locations of the garter springs. Other factors such as feeder pipes and axial compressive loads also contribute but are less significant.

Dependence on GS locations arises because the springs provide the only dynamic coupling between the PT and CT. This coupling ties the vibrations of the two tubes together, giving rise to resonances which are characteristic of the complete fuel channel rather than just the individual components.

2.1.0 *Experiments*

Experiments have been carried out on the Bruce B mock-up fuel channel to characterize its low frequency beam vibrations. Objectives were

- to determine the frequency response functions (FRF) and resonant mode shapes
- to determine the sensitivity to garter spring positions
- to appraise the possibility of extracting useful information about the GS locations, given access only to the end fittings

All tests were conducted with fuel, PHT water, shield and closure plugs in place. Because of the excessive dynamic coupling to the trough discovered earlier [4], the moderator trough was removed.

The four garter springs were placed in various locations to reveal their influence on the channel dynamics. For most of the tests the two central spacers were pinched. However, the two outer spacers were usually loose or weakly pinched because of the lack of buoyancy provided by moderator water.

Excitation for all tests was provided by an electrodynamic shaker, driven by a swept-sine signal through the frequency band of interest. Initial tests, to determine the FRF's and mode shapes, were conducted with the force applied directly to the PT or CT. Recognizing that on a reactor one would have access only to the end fittings, later tests were conducted with the force applied to each end fitting, in turn.

2.1.1 *Resonant Modes and Damping*

The initial objective was to determine the basic character of the beam vibrations induced by controlled excitation of the PT or CT. This was done with the garter springs in their design locations. By applying the vertical driving force about 2 m from the centre-line it was possible to excite all resonant modes of interest.

A slow sweep (1 Hz/s) from 3 - 100 Hz revealed three major resonances (Figure 1). The fundamental vibration mode, a single loop with the PT and CT essentially locked together, is at about 6.6 Hz. For the second harmonic, at 15.5 Hz, the PT and CT again have similar mode shapes. However, the amplitude of the CT vibration is only about one half of the PT amplitude. The third harmonic, at about 24 Hz, has the CT vibrating in a single loop while the PT has three loops.

The FRF, defined as the ratio of acceleration over force at the driving location, showed that the first two modes are very lightly damped. As the frequency increases, however, so does the damping - to the extent that by 30 Hz all detail in the spectral response is effectively smeared.

End fitting vibrations were found to follow the PT but with greatly reduced amplitude. At 6.6 Hz the acceleration was reduced by a factor of 200 and at 15.5 Hz by a factor of 20. At higher frequencies the EF vibrations appeared to be dominated by resonances of the end fittings themselves, the feeder pipes, and related hardware. Damping of these EF modes was much less than for the PT - CT modes.

An extremely slow sweep of the driving signal through the 6.6 Hz resonance showed it to have a width of 0.006 Hz centred at 6.590 Hz, and hence a Q of 1000. The 15.5 Hz mode is about 0.1 Hz wide, with a Q of 200.

2.1.2 *Dependence of FRF on Garter Spring Locations*

From the experiments described above, it was clear that measurements of EF vibrations would reveal only the first two resonant frequencies. If useful information regarding GS locations was to be obtained then it would have to come from shifts of these two modes. Moving one of the two (pinched) central spacers 0.5 m outboard caused the 15.5 Hz resonance to shift upwards 0.5 Hz (Figure 2). Any shift in the 6.6 Hz mode could not be detected with the resolution (0.1 Hz) of that test. Theoretical results relating resonant frequencies to GS location are discussed later.

An attempt was made to completely decouple the vibrations of the PT and CT. The garter springs were moved outboard sufficiently far that none was pinched. Shifts of about 1 Hz were observed in the resonant frequencies. However, there was clearly still strong coupling between the PT and CT. To eliminate an apparent contact between the tubes near the mid-point, weights were placed on the CT. This changed the spectrum again, but did not eliminate the coupling. Considerable further effort failed to decouple the PT and CT vibrations, although numerous different spectra were obtained indicating varying degrees of coupling.

2.1.3 *Non-Invasive Measurement of Resonant Frequencies*

By exciting the PT and CT directly it was possible to obtain a clear picture of the resonant modes and their dependence on GS locations. Such direct excitation would not, however, be possible in a non-invasive inspection method. Given access only to the end fittings, one would have to both apply the driving force and measure the response on the end fittings.

The best results should be achieved with the excitation applied to one end fitting and the response acceleration measured at the opposite end. The coupled PT and CT would then act as a mechanical filter, with poles at the resonant frequencies identified above.

Tests were performed to see whether such measurements can be reliably used to determine the resonant frequencies of the fuel channel beam vibrations. With the shaker fastened at one end of the mock-up fuel channel it was possible, by driving at the known resonant frequencies, to excite both the 6.6 Hz and 15.5 Hz modes. The mode shapes were as found in the earlier tests, as was the acceleration measured at the far end of the channel.

When the driving signal was a swept-sine, however, only the 6.6 Hz mode could be clearly identified in the far end acceleration (Figure 3). The 15.5 Hz peak was present, but could not be distinguished from new complex structure in the response spectrum ranging from 15 Hz up. This new structure was apparently due to resonant behaviour of the end fittings, feeder pipes, and other associated hardware. Various attempts to remove the end fitting noise were not successful.

2.2.0 *Analytical Model*

The tedious experimental procedures involved with measurement of the beam vibration characteristics prompted the development of an analytical model. A fuel channel can be effectively represented as a collection of simple beams tied together with an appropriate geometry (Figure 4). Each span between support points or garter springs is a separate beam. Thus each end fitting is modelled by two beams - the end portion and the part between bearings - joined rigidly together. In a four-spacer channel, the pressure tube is modelled by five beams connected rigidly in series, with an end fitting fastened rigidly on each end. Similarly, the calandria tube is modelled by five beams in series, with clamped ends.

Bearings and garter springs are represented by simple springs. The bearings are stiff springs tied to ground. The garter springs are relatively soft springs which link the PT and CT motions, at their respective beam joints.

Fuel, plugs, and PHT water are treated as distributed masses. No provision is made for moderator or feeder pipes. Forces can be applied at the ends of any constituent beam.

The vibration problem can be formulated and solved in closed form, providing for structural and frictional damping, axial loads, and forces of arbitrary magnitude and frequency. For the four-spacer channel there are a total of 14 simple beams, leading to a set of 112 linear equations which represent the boundary conditions. Computer programs have been developed to set up and solve these equations, and produce graphical output equivalent to the processed experimental data.

Poorly known parameters, such as the bearing stiffness and damping coefficients, were determined by direct comparison between computed and measured results. In this way the model could be tuned to accurately represent the mock-up fuel channel. Once tuned, parameters such as GS locations, axial load, and bearing stiffness could be varied to determine the sensitivity of computed spectral responses. In addition, the model provided pictures of vibration mode shapes which could not be obtained by experiment because of limited access to the PT.

Since the model can be applied to general systems of beams under tension or compression it was also tested on a completely unrelated problem - vibration of overhead electrical conductors. Model results for this problem matched available experimental data with extremely good accuracy, confirming the validity of the computer programs.

2.2.1 *Model Results*

Fuel channel models with both two and four spacer configurations were studied. The two spacer model was used to tune the adjustable parameters. In simulations of the experimental tests with the force applied directly to the PT, PT-CT resonances were predicted at 6.4, 15.8, and 27 Hz. End fitting modes were predicted at about 21 Hz (Figures 5,6).

The first two predicted frequencies closely match the measured values. Inaccuracy of the model at higher frequencies, possibly due to motion of the tube sheets, is indicated by the 3 Hz deviation of the third mode from the measured frequency. The qualitative form of the predicted FRF is very similar to the measured FRF. Predicted end fitting resonances match the gross behaviour of the observed EF vibrations, but fail to reveal the complexity created by the feeder pipes and other hardware.

With four garter springs in their design locations the PT-CT resonant frequencies shifted upward by varying amounts (Figures 7,8). The fundamental was least affected since the PT and CT were already moving almost in unison. For the second harmonic the increased coupling shifted the resonance upward to 17 Hz, with the PT and CT motions more closely matched. The third harmonic suffered the greatest change, with its frequency moving to 30 Hz, and the mode shape of the CT changing from one to three loops.

In model tests with the force applied at one end fitting, the vibration induced at the far end showed the PT-CT resonances, but with a very small amplitude (Figure 9). This was also consistent with measured data.

A compressive load of 1000 N on the PT and end fittings had negligible influence on the predicted mode-shapes and frequencies. Changing the bearing spring constants by a factor of 10 also had very little effect on the first two resonant frequencies, although it did change the shape of the FRF.

Since several different kinds of damping are incorporated in the model it was difficult to fix precise values for the damping coefficients. However, the widths of the first two modes could be readily adjusted to match measurements. At higher frequencies, though, the actual damping seems to increase faster than could be predicted with the linear model.

For the two spacer model, moving one GS outboard as in the experimental program, served to lower the 6.4 Hz mode very slightly and raise the second harmonic by about 0.4 Hz. These results were consistent with the measured data.

3.0 *DISCUSSION*

Deviations of the garter springs from their design locations have been shown to produce changes in the resonant frequencies of beam vibrations. The fundamental mode is very narrow (0.006 Hz) and so even a 0.1 Hz shift could be significant. The second harmonic could be expected to shift down by 0.5 Hz or more from the nominal value of 17 Hz for a four spacer channel. Similarly the third harmonic could shift down by several Hertz.

The difficulty is that these resonant frequencies must be determined through measurement of end fitting vibrations. Experiments have shown that the end fittings become active at about 15 Hz, with a major resonance at about 21 Hz. The complexity of the end fitting spectra above 15 Hz can be attributed largely to the feeder pipes, restraining bolts, and other hardware. Different spectra were measured on the two ends of the mock-up fuel channel and one should expect further differences amongst the channels of a

reactor.

In spite of the differences in their spectral responses, the vibrations of the two end fittings are strongly coherent - that is, a major component of their accelerations is phase-locked. This means that signal averaging techniques do not suppress the EF modes relative to PT-CT resonances.

If it were possible to apply the driving force directly to the PT or CT then the second, and possibly third, PT-CT resonance could be measured at the end fittings. In that case, major deviations of the garter springs from their design locations could be reliably flagged, while shifts of 0.5 m or less could be identified, given a reference spectrum. However, the non-invasive requirement for the inspection technique precludes such excitation.

4.0 *SUMMARY AND RECOMMENDATIONS*

While it is now apparent that the resonant frequencies of a fuel channel can provide useful information about GS locations, the problem remains that only the end fittings are physically accessible. The stiff bearings which support the channel effectively decouple the end fitting vibrations from those of the pressure and calandria tubes. Except for the fundamental mode, the resonant frequencies of interest cannot be reliably determined through non-invasive methods.

The frequency of the fundamental beam vibration mode is not considered to be a sufficiently reliable indicator of correct/incorrect GS locations to justify continued development work.

Previous reports have described diverse efforts to develop a non-invasive inspection technique based on the measurement and analysis of higher frequency vibrations. The frequency spectrum has now been studied from 3 Hz to 200 kHz - the full range accessible to practical measurement.

It is recommended that:

- no further attempts be made to develop a non-invasive inspection technique based on analysis of fuel channel beam vibrations
- the entire NILOCS project be terminated, with any future development work relying on ingress techniques.

Reviewed by:

M.P. Dolbey
Senior Research Engineer
Metallurgical Research Department

Prepared by:

P.G. Buchan
Engineer
Transmission and
Special Projects Section

Approved by:

for A.F. Baljet
Manager
Electrical Research Department

M.A. Green
Physicist
Transmission and
Special Projects Section

PGB/MAG:mag

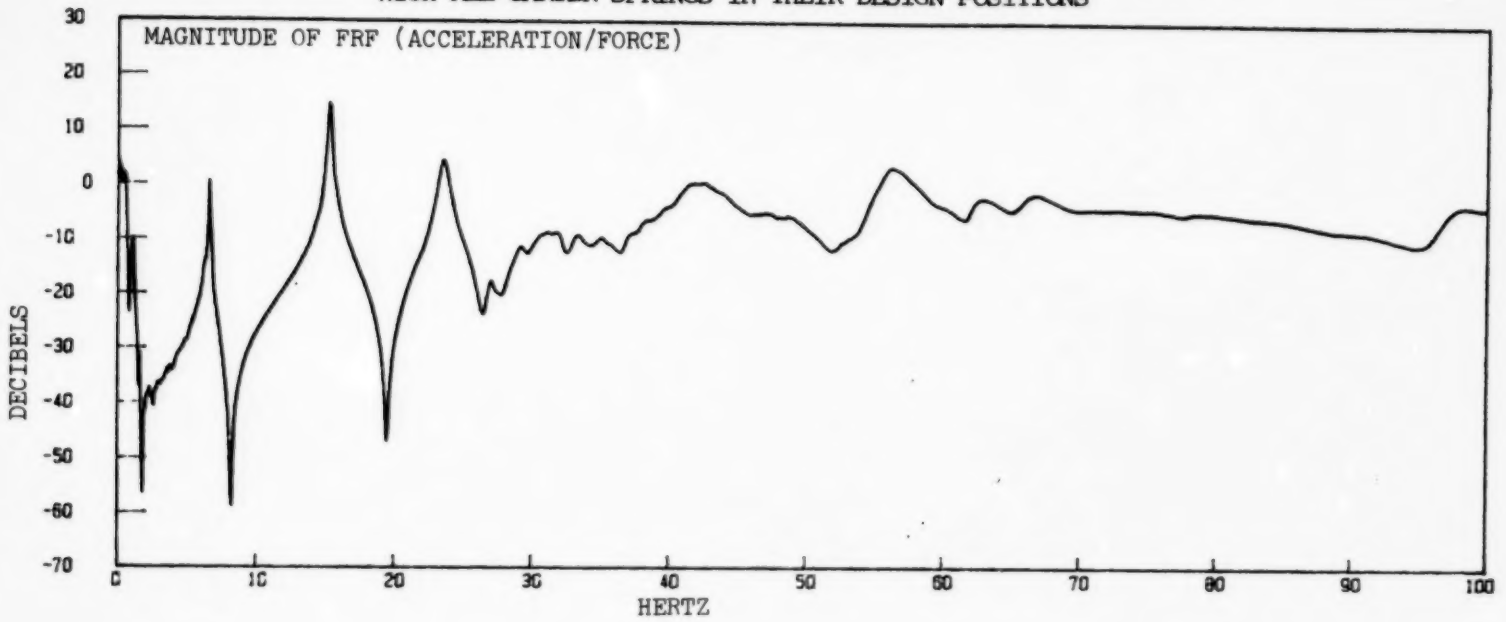
REFERENCES

1. Buhay, S., "Non-Invasive Location of Channel Spacers Using Acoustic Emission Techniques - Pickering A Fuel Channel", OHRD Report No M84-142-K, November 14, 1984.
2. Baron, J.A. and S. Buhay, "Acoustic Emission and Adaptive Learning Techniques for the Location of an Impact Source", OHRD Report No M85-61-K, January 29, 1986.
3. Buchan, P.G. and M.A. Green, "Non-Invasive Location of Channel Spacers (NILOCS) - Recent Progress", OHRD Report No 85-325-K, November 15, 1985.
4. Buchan, P.G. and M.A. Green, "Non-Invasive Location of Channel Spacers (NILOCS) Using Generalized Cross-Correlation Techniques - Final Report", OHRD Report No 86-42-K, February 19, 1986.
5. Chisholm, W.A. and M.A. Green, "Pressure Tube - Calandria Tube Contact: Analysis of Vibration Diagnostic Techniques", OHRD Report No 84-72-H, March 2, 1984.
6. "An Evaluation of Non-Invasive Garter Spring Location Using Vibration Analysis", memo from T. Loewen to J. Graham, April 12, 1984, File 825.53.

7. Liska, J.J., "Non-Invasive Monitoring of Fuel Channel Condition (NIMOCC)", OHRD Report No 86-149-K (DRAFT).

FIGURE 1

RESPONSE OF PRESSURE TUBE TO FORCED, SLOW SWEEP, VIBRATIONAL EXCITATION
WITH ALL GARTER SPRINGS IN THEIR DESIGN POSITIONS



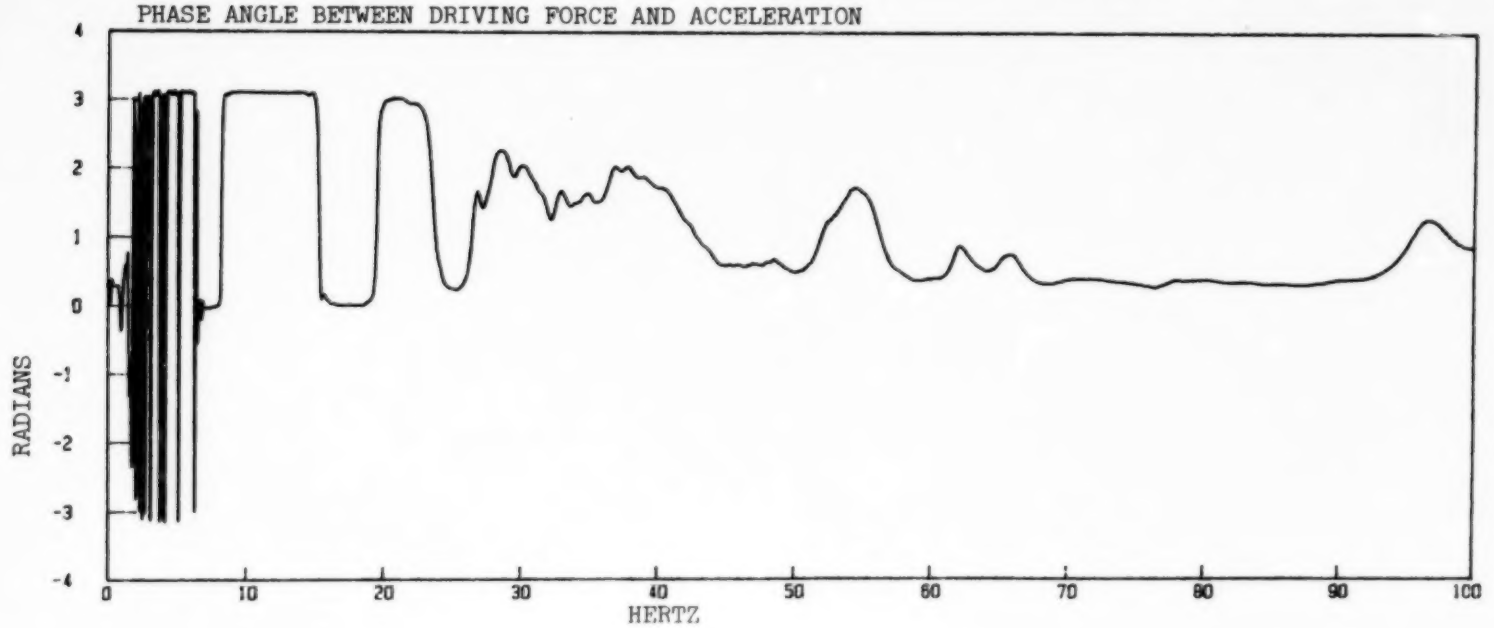
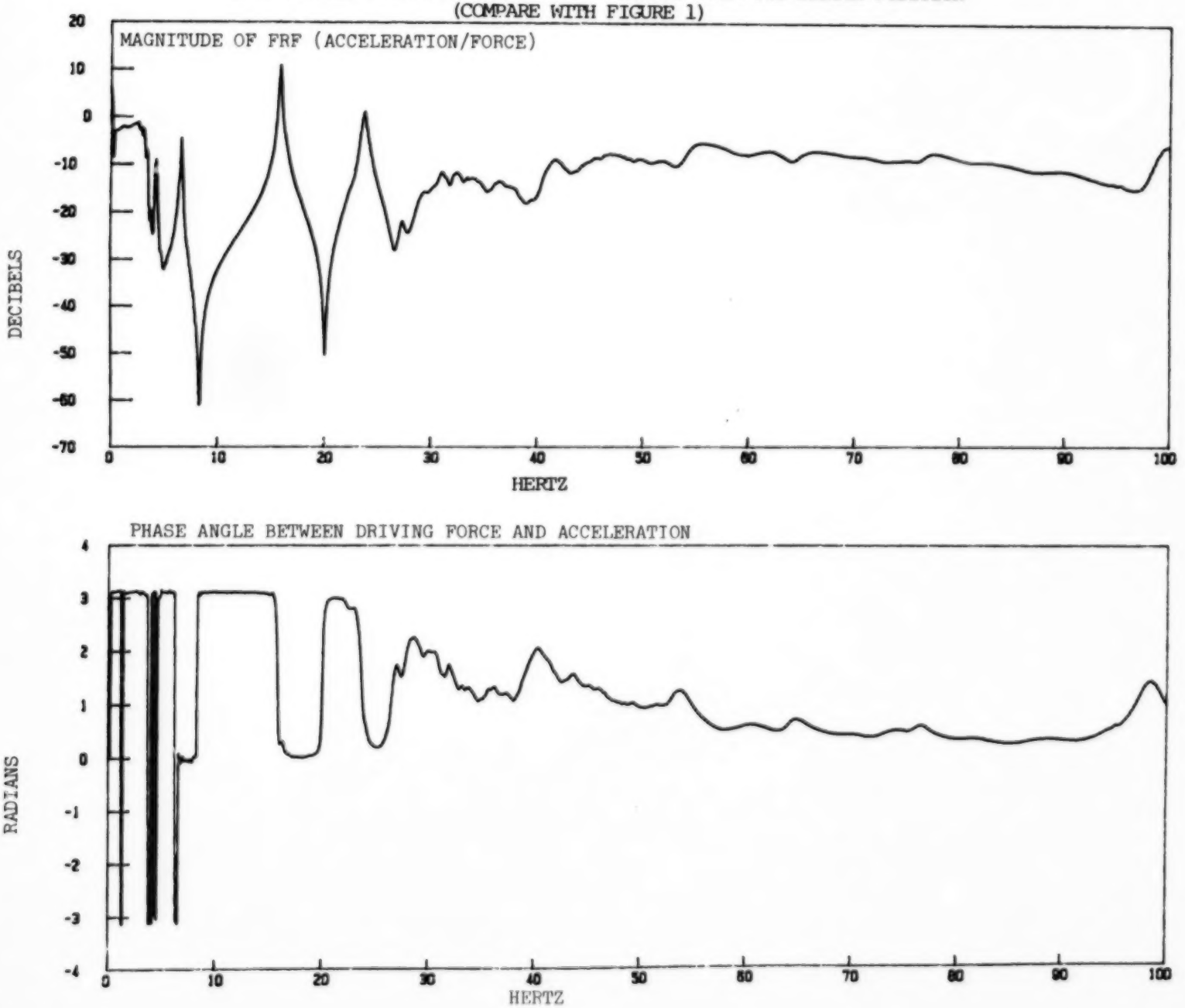
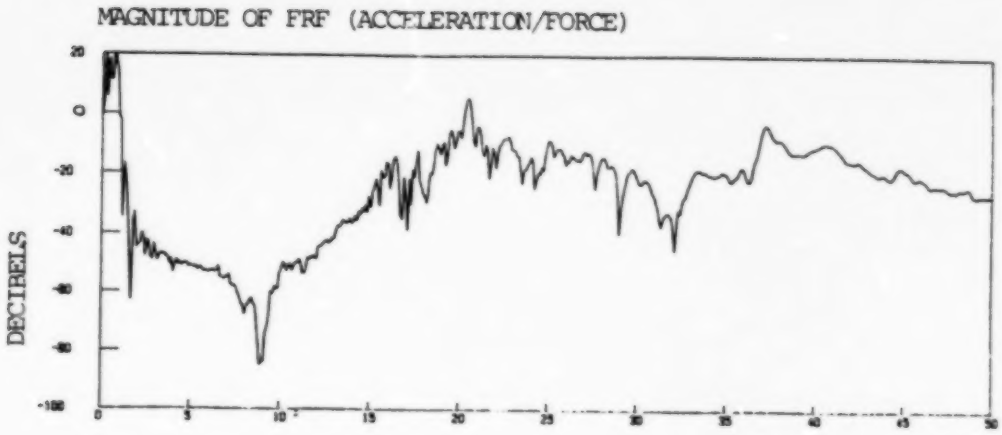
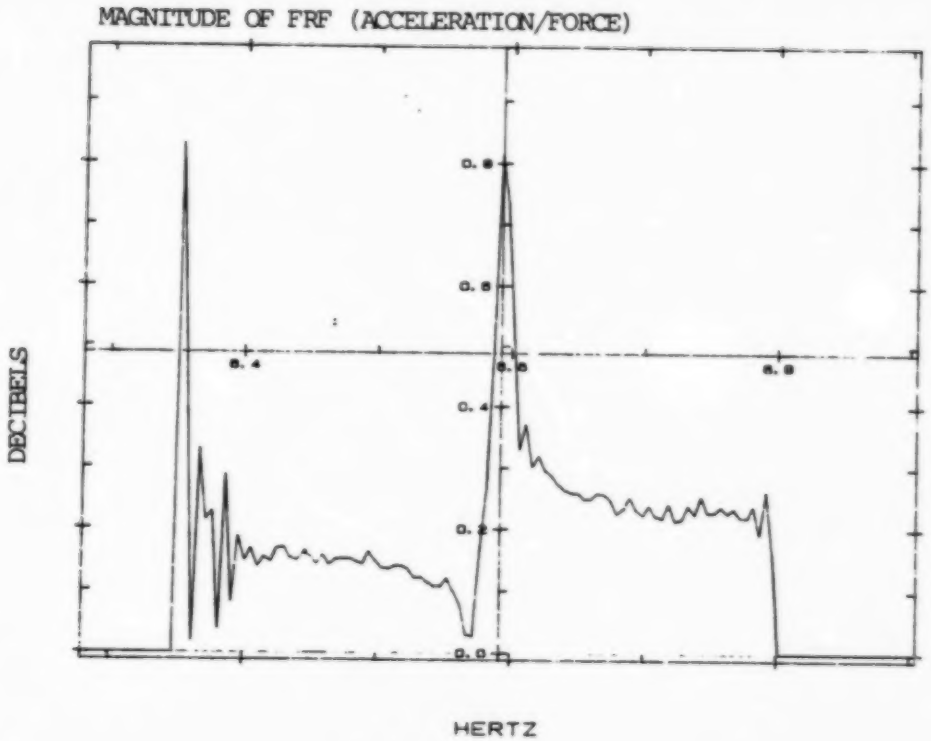


FIGURE 2
RESPONSE OF PRESSURE TUBE TO FORCED, SLOW SWEEP, VIBRATIONAL EXCITATION WITH ONE OF FOUR GARTER SPRINGS SHIFTED 0.5 METRES FROM ITS DESIGN POSITION
(COMPARE WITH FIGURE 1)







HIGH RESOLUTION MEASUREMENT BETWEEN 6.4 AND 6.8 HERTZ

FIGURE 3

VIBRATIONAL RESPONSE OF ONE END FITTING TO FORCED, SLOW-SWEEP VIBRATIONAL EXCITATION OF THE OPPOSITE END FITTING

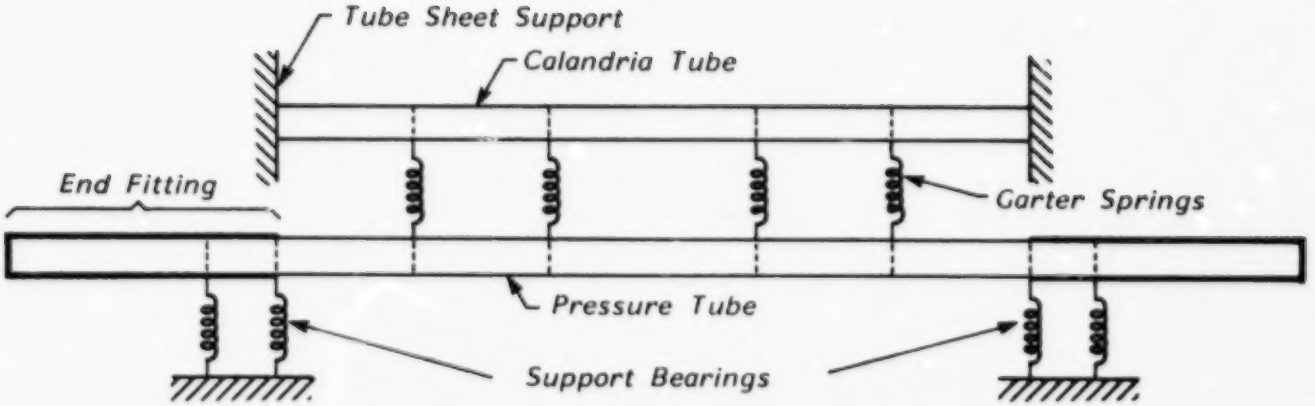


FIGURE 4

SIMPLIFIED BEAM MODEL OF A CALANDRIA AND PRESSURE TUBE ASSEMBLY

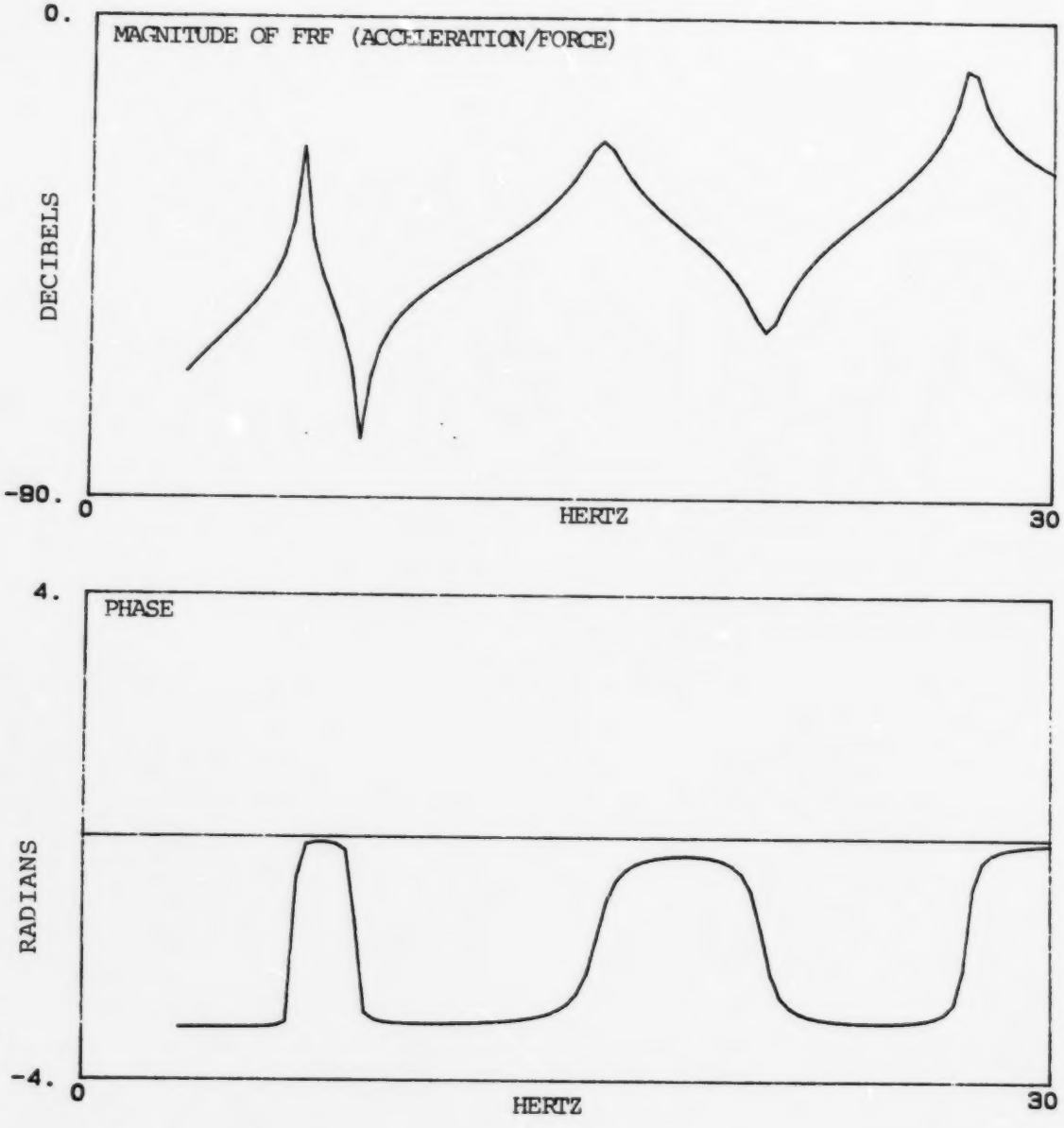
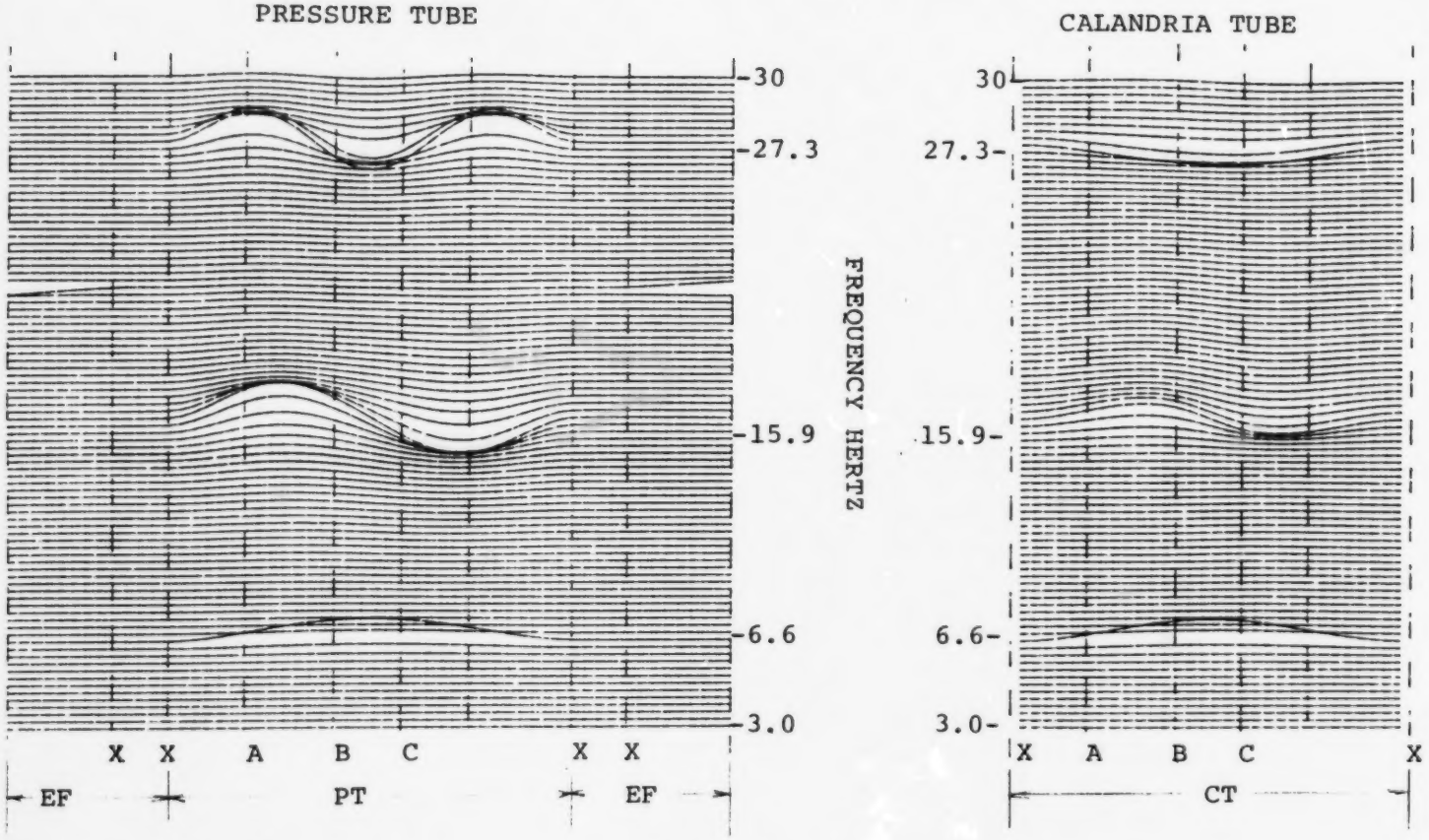


FIGURE 5

COMPUTED RESPONSE OF PRESSURE TUBE TO FORCED EXCITATION
WITH TWO CENTRAL GARTER SPRINGS IN DESIGN POSITION



EF - End Fitting
PT - Pressure Tube
CT - Calandria Tube
X - Bearing
B,C - Garter Spring Positions
Vibrational Force Applied at A to PT

Figure 6

Mode Shape Versus Frequency with Two Central Garter Springs in Design Position

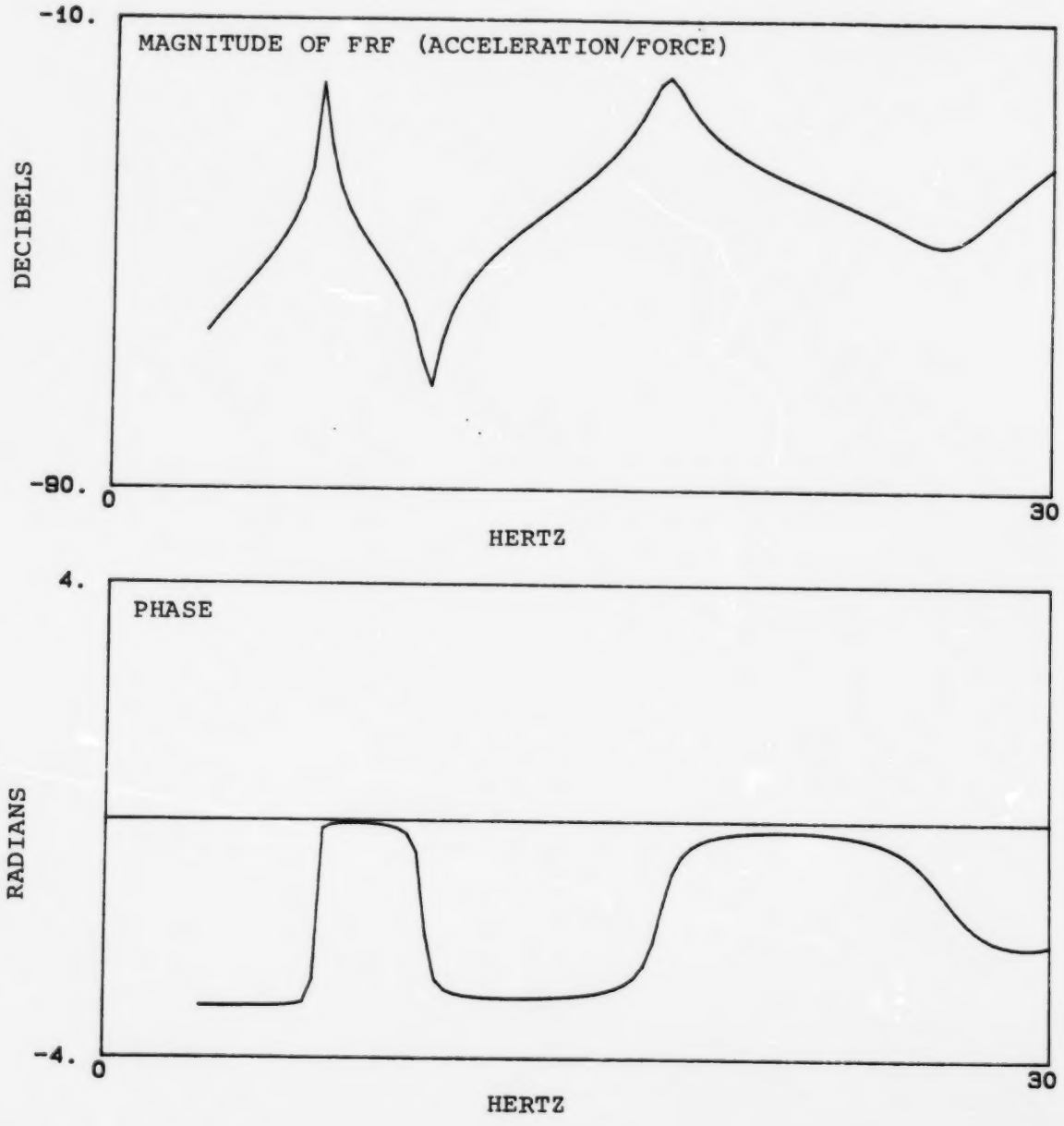
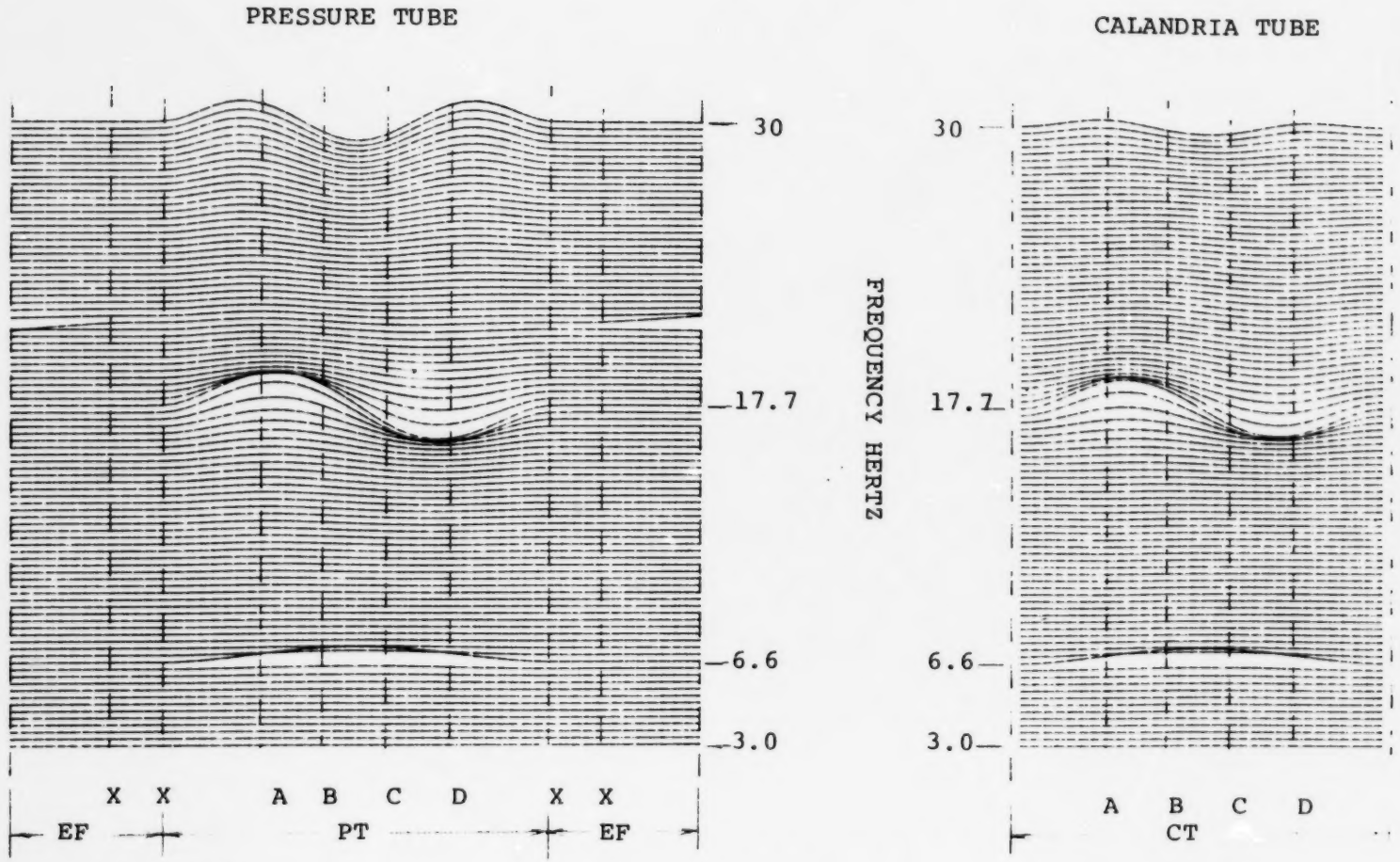


FIGURE 7

Computed Response of Pressure Tube at
Point of Excitation with Four Garter Springs
in Design Position (Compare with Figure 5)



EF - End Fitting
PT - Pressure Tube
CT - Calandria Tube
X - Bearing
A,B,C,D - Garter Spring Positions
Vibrational Force Applied at A to PT

Figure 8

Mode Shape Versus Frequency with Four Garter Springs in Design Position

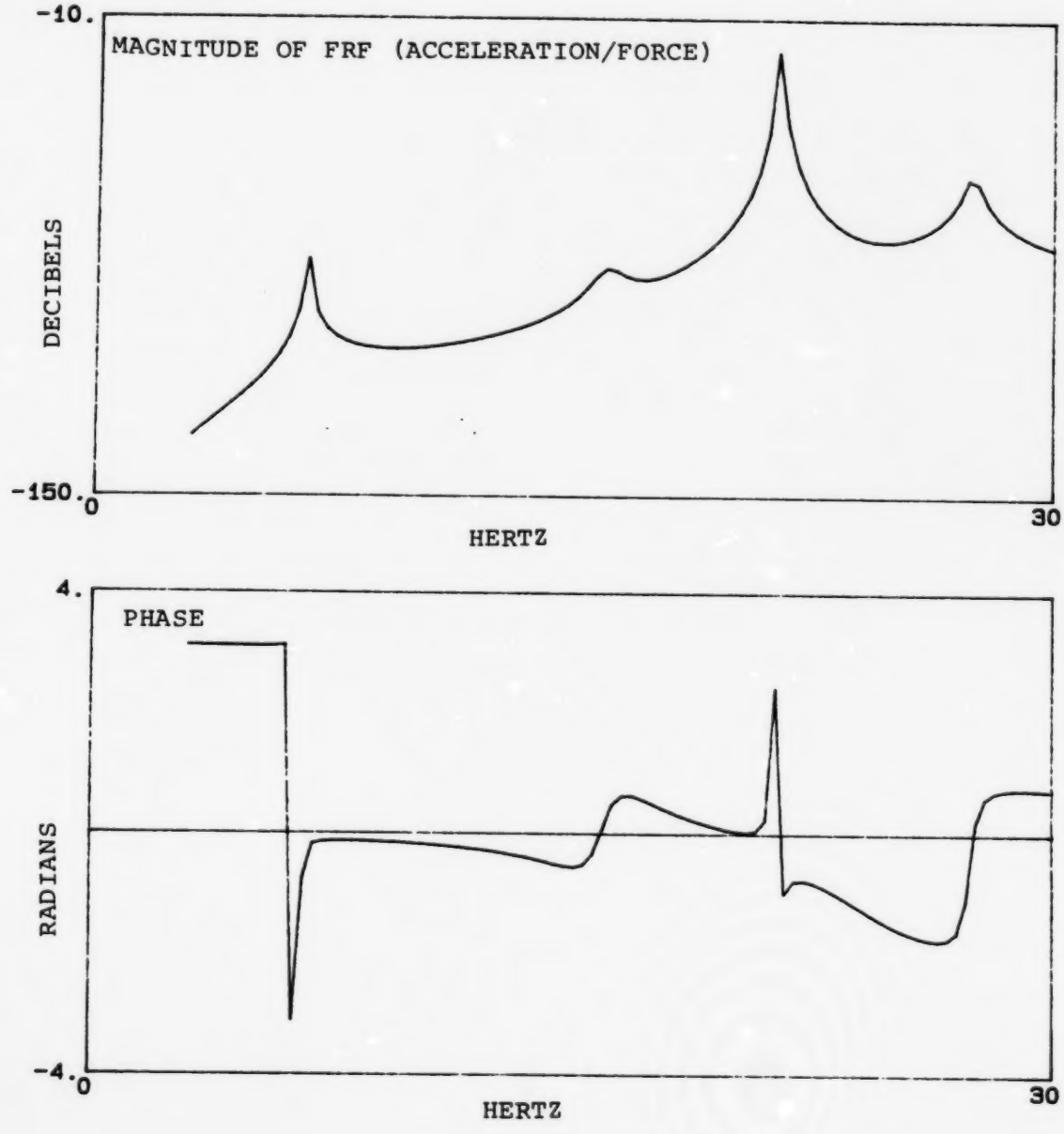


FIGURE 9

Computed End Fitting-to-End Fitting
Response with Two Central Garter
Springs in Design Position